W boson polarization measurement in the $t\bar{t}$ dilepton channel using the CDF II Detector

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We present a measurement of W boson polarization in top-quark decays in $t\bar{t}$ events with decays to dilepton final states using 5.1 fb^{-1} integrated luminosity in $p\bar{p}$ collisions collected by the CDF II detector at the Tevatron. A simultaneous measurement of the fractions of longitudinal (f_0) and right-handed (f_+) W bosons yields the results $f_0 = 0.71^{+0.18}_{-0.17}(\text{stat}) \pm 0.06(\text{syst})$ and $f_+ = -0.07 \pm 0.09(\text{stat}) \pm 0.03(\text{syst})$. Combining this measurement with our previous result based on single lepton final states, we obtain $f_0 = 0.84 \pm 0.09(\text{stat}) \pm 0.05(\text{syst})$ and $f_+ = -0.16 \pm 0.05(\text{stat}) \pm 0.04(\text{syst})$. The results are consistent with standard model expectation.

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Since the top quark discovery by the CDF and D0 experiments in 1995, many of its properties have been measured. Due to its very short lifetime, the top quark does not hadronize and therefore its properties are transferred directly to its decay products. The standard model (SM) makes specific predictions for the W-boson polarization in top-quark decays. Precise measurement of the W-boson polarization fractions provides a test of the SM and could reveal new physics beyond the SM [1].

In the SM, the top quark decays to a W boson and b quark with almost 100% probability [2]. The W boson is a massive vector particle with three polarization states: right-handed (+1), longitudinal (0), and left-handed (−

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1). The differential decay rate is given by:

$$\frac{d\Gamma}{d\cos\theta^*} \propto (1-c)^2 f_- + 2(1-c^2) f_0 + (1+c)^2 f_+ \quad (1)$$

where $c \equiv \cos\theta^*$, and the polarization angle θ^* is the angle between the direction of the charged lepton (or down-type quark) and the opposite of the direction of the top quark in the W boson rest frame. The polarization fractions satisfy the normalization condition $f_- + f_0 + f_+ = 1$. Right-handed W boson production is strongly suppressed due to the $V-A$ structure of the charged-current weak interaction. In the SM at tree level [1], the fraction of right-handed W bosons is very close to zero ($f_+ = 3.7\times10^{-4}$) while $f_0 = 0.698$, and $f_- = 0.301$ for a top-quark mass of 173.3 GeV/c^2 [3], W-boson mass of 80.4 GeV/c^2 [2], and a b-quark mass of 4.78 GeV/c^2 [2]. In the $m_b \to 0$ limit, $f_+ = 0$ and $f_0 = m^2_{\rm top}/\left(2m^2_W + m^2_{\rm top}\right)$. Polarization fractions that deviate from the SM are predicted in theories with anomalous tWb couplings [1].

Earlier measurements of the polarization fractions of the W boson in top-quark decay by the CDF and D0 collaborations focused on the single-lepton channel [4, 5]. Currently, the most precise result has been reported by the D0 collaboration, where the combination of single lepton and the dilepton channels has been performed [5]. In this Letter we report the CDF measurement in the dilepton channel ($t\bar{t} \to W^+bW^-\bar{b} \to \ell^+\nu b\ell^-\bar{\nu}\bar{b}$). We perform two types of measurements: a model-independent approach where f_0 and f_+ are determined simultaneously; and a model-dependent approach where f_0 (f_+) is fixed to its SM value, and f_+ (f_0) is measured. The model-independent and model-dependent approaches are referred as "2D" and "1D", respectively, throughout this article. We also combine this result with our previous measurement [4] in the single-lepton channel.

This analysis is based on data corresponding to an integrated luminosity of 5.1 fb^{-1} collected with the CDF II detector [6] between March 2002 and June 2009 at the Fermilab Tevatron with a center of mass energy $\sqrt{(s)}$ = 1.96 TeV. The CDF II detector is described in detail elsewhere [6]. The components essential to this analysis are the tracking system consisting of a silicon microstrip tracker and a central drift chamber immersed in a 1.4 T solenoidal magnetic field; electromagnetic and hadronic calorimeters arranged in a projective geometry outside the magnet coil; and drift chambers and scintillation counters for muon detection outside the calorimeters.

The analysis uses the same event selection criteria that are used for the measurement of the $t\bar{t}$ cross-section in the dilepton channel [7]. A brief description of the event selection is as follows: the data are collected with an on-line inclusive event-selection system (trigger) that requires a high transverse energy E_T [8] lepton (electron or muon with $E_T > 18$ GeV [9]). From the inclusive lepton data, we selected events with opposite-charged leptons of $E_T > 20$ GeV. We require the first lepton to be well identified and isolated, while the second lepton is more loosely identified and has no isolation requirement. The pseudorapidity η [8] coverage is $|\eta| < 2.0$ for electrons and $|\eta| < 1.0$ for muons. We require missing transverse energy $\not\!\!E_T > 25$ GeV [10] unless the $\not\!\!E_T$ direction is along (within 20° in ϕ) either a lepton or a jet, in which case we require $\not\!\!E_T > 50$ GeV. Additionally we require at least two jets [11] reconstructed with $E_T > 15$ GeV and $|\eta| < 2.5$. Jet energies are corrected for the effects of calorimeter response, multiple interactions, and the hadronic calorimeter energy scale [12]. Backgrounds to the dilepton signal are further reduced through kinematic cuts on the dilepton invariant mass, total energy in the transverse plane and $\not\!\!E_T$ significance. For the purpose of this measurement, we split the inclusive data sample into two non-overlapping subsamples ("b-tag" and "non-tag") where for the "b-tag" subsample we require at least one jet in the event to be consistent with having originated from a b quark by using an algorithm that identifies a long-lived b hadron through the presence of a displaced vertex [13]. The two subsamples have different signal to background ratios and background compositions; therefore, we can improve the overall measurement uncertainties by analyzing each subsample separately.

The dominant background to $t\bar{t}$ dilepton events is from "fake" events where a jet is misidentified as a lepton. The main source of "fake" events are $W(\to \ell\nu)$ + jets events. The additional background is Drell-Yan production of electrons and muons ($q\bar{q} \to Z/\gamma^* \to \ell^+\ell^-$, where $\ell = e, \mu$) with the fake $\not\!\!E_T$. Both of the above backgrounds are estimated using data-based methods. The remaining backgrounds are from Drell-Yan production of τ leptons and SM diboson (WW,WZ,ZZ) production which are estimated using Monte-Carlo (MC) simulation. The detailed description of the background estimation can be found in [7]. The number of events expected and observed passing dilepton selection is presented in Table I. The uncertainties on the number of events include the statistical and systematic part. The correlations between signal and various backgrounds systematic uncertainties are taken into account. There is good agreement between data and the expectation from $t\bar{t}$ and backgrounds.

We use the $\cos\theta^*$ of the leptons defined above to determine the W boson polarization fractions. In order to reconstruct $\cos\theta^*$, the full $t\bar{t}$ kinematic chain must be reconstructed. The dilepton channel presents an underconstrained system due to the two undetected neutrinos. We use a simple modification of the kinematic method previously developed for the measurement of the top-quark mass, denoted as the KIN method in [14]. We solve the kinematic equations by Newton's method for nonlinear systems of equations using the top-quark mass constraint with $m_{top} = 175$ GeV/c^2. In principle each event provides two measurements of $\cos\theta^*$; in practice, the re-

TABLE I: Expected and observed number of signal and background events after the dilepton selection assuming $\sigma_{t\bar{t}} = 6.7$ pb ($m_{top} = 175$ GeV/c^2).

Source	Events
Diboson	17.45 $\pm$ 4.64
$Z/\gamma^* \rightarrow \tau\tau$	12.26 $\pm$ 2.18
$Z/\gamma^* \rightarrow ee + \mu\mu$	22.40 $\pm$ 3.24
Fakes	53.69 $\pm$ 14.71
Total background	105.80 $\pm$ 17.24
$t\bar{t}$ ($\sigma = 6.7$ pb)	222.44 $\pm$ 10.61
Total SM expectation	328.24 $\pm$ 27.61
Observed	343

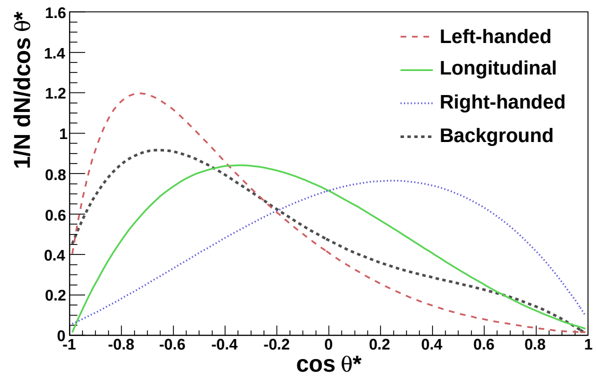

FIG. 1: The signal templates for left-handed, longitudinal and right-handed W bosons together with the background template for the inclusive dilepton selection.

construction under our assumptions can fail in which case we don't consider such event.

In order to perform the fit to the $\cos\theta^*$ distribution we create templates using $t\bar{t}$ MC simulated samples for exclusive left-handed, longitudinal and right-handed W bosons using a customized HERWIG [15, 16] MC generator. We create the templates separately for b-tag and no-tag subsamples which turn out to be similar. Figure 1 shows the templates for the inclusive sample for both the signal and background.

Due to various selection and reconstruction effects (e.g., we consider the two highest E_T jets as jets coming from b-quark hadronization while there is a possibility that one of these two jets comes from initial (ISR) or final (FSR) state gluon radiation) the templates vary significantly from the theoretical distributions in Eq. (1). The effect of the lepton isolation cut is seen as a softening of the theoretical peaks near $\cos\theta^* = -1$. Furthermore, the KIN reconstruction method requires the lepton-jet-$\not{E}_T$ mass to be close to the mass of the top quark so that the reconstruction is inefficient for high lepton-jet pair masses ($\cos\theta^* \simeq +1$). This gives a polarization-dependent reconstruction efficiency of about 95%, 92%, and 87%, respectively, for left-handed, longitudinal, and right-handed W bosons. For the background events, the reconstruction efficiency is only 71%. There are also differences in the acceptance of dilepton events. The largest difference is between events with two left-handed W bosons where the acceptance is about 30% smaller relative to the acceptance of events having two longitudinal W bosons. This is mainly due to the dependence of the acceptance on the lepton p_T and isolation (leptons from left-handed W bosons tend to be less isolated and have smaller p_T).

We combine the signal and background templates taking into account the above W polarization dependent efficiencies. We use an unbinned likelihood method which determines the f_0 and f_+ polarization fractions that best correspond to the observed $\cos\theta^*$ distribution. The Gaussian constraint on the number of background events and the Poisson constraint on the total number of events are included in the likelihood formula. We multiply the likelihoods for "b-tag" and "non-tag" subsamples to arrive at the final likelihood. The method has been extensively tested in simulated samples across a full range of physically possible values of f_0 and f_+ parameters. From these tests, we obtain small corrections to the measured values of f_0 and f_+.

The determination of W boson polarization fractions by our method is sensitive to different sources of theoretical and experimental uncertainties, such as the MC simulated templates, the jet reconstruction algorithms, and jet corrections. We have performed MC studies of simulated experiments in order to estimate these systematic uncertainties. One of the largest sources of systematic uncertainty comes from the jet energy scale (JES). We have studied this uncertainty by changing the corrections by $\pm1\sigma$ of the JES uncertainty [12]. Another large systematic uncertainty is modeling of the signal which we estimate as variations in the ISR and FSR, using different parton distribution functions (PDF) and different MC generators (see [7] for details). We estimate the systematic uncertainty due to the background template shape by changing each individual background within its rate uncertainty thus changing the overall shape. We then combine all these shifts (in quadrature) to obtain an overall background shape uncertainty. The uncertainty in the total number of expected background events is taken into account in the fitting procedure where the amount of background is allowed to float. The method-specific systematic uncertainties are due to limited statistics of the signal and background templates and are evaluated by fluctuating the templates bin-by-bin. An additional (small) uncertainty is due to the instantaneous luminosity which determines the mean number of interactions per bunch crossing. The systematic uncertainties are summarized in Table II, with the total systematic uncertainty of the measurement being the sum in quadrature of all the partial systematic uncertainties from the various sources.

TABLE II: Summary of systematic uncertainties.

Source	Δf_0^{1D}	Δf_+^{1D}	Δf_0^{2D}	Δf_+^{2D}
Jet energy scale	0.033	0.019	0.002	0.020
Generators	0.035	0.019	0.016	0.011
ISR/FSR	0.024	0.010	0.040	0.017
PDF	0.010	0.003	0.025	0.009
Background shape	0.012	0.005	0.023	0.010
Template statistics				
Signal	0.010	0.005	0.024	0.012
Background	0.007	0.004	0.015	0.007
Instant. luminosity	0.016	0.008	0.013	0.002
Total	0.059	0.031	0.063	0.034

We assume a fixed top-quark mass of $m_{top} = 175$ GeV/c^2 in our dilepton measurement. However, as already noted, within the SM the fraction of W bosons with a given polarization directly depends on the top-quark and W-boson masses. Therefore, we do not include this effect in the systematic uncertainties. Rather, we provide the m_{top} dependence of the reconstructed fractions. We estimate that there is a linear shift in reconstructed f_0 (f_+) of ±0.004 (±0.005) and ±0.012 (±0.006) per ±1 GeV/c^2 change in the top-quark mass for 2D and 1D measurements, respectively.

There are 304 events (118 in "b-tag" and 186 in "non-tag" subsamples) passing dilepton selection and kinematic reconstruction, consistent with the SM expectation of 284.3 ± 22.7 events. The comparison of $\cos\theta^*$ between data and the expectations for SM $t\bar{t}$ signal and background can be seen in Fig. 2. There is a good agreement between data and the SM expectation ($\chi^2 = 6.5$ for 9 degrees of freedom, corresponding to a p-value of 69%).

We perform a model-independent simultaneous determinations of both f_0 and f_+ fractions: $f_0 = 0.71^{+0.18}_{-0.17}$(stat) and $f_+ = -0.07 \pm 0.09$(stat). There is a strong negative correlation of -0.88 between the statistical uncertainties of f_0 and f_+. We also measure each polarization fraction when the other is fixed to its SM value. We measure $f_0 = 0.59 \pm 0.09$(stat) when f_+ is so fixed and measure $f_+ = -0.07 \pm 0.04$(stat) when f_0 is so fixed. We also find $f_+ < 0.07$ at 95% C.L. when f_0 is so fixed following Bayesian procedure assuming constant a priori probability for the f_+ within physically possible range.

The CDF measurement performed in the single lepton channel obtained the following result [4], assuming a top-quark mass 175 GeV/c^2: $f_0 = 0.88 \pm 0.11$(stat) $\pm$ 0.06(syst) and $f_+ = -0.15 \pm 0.07$(stat) $\pm$ 0.06(syst) with the correlation of –0.6 between f_0 and f_+. This is consistent with the result presented in this Letter. We combine both results using the analytic best linear unbiased estimator method [17, 18]. When combining these results, in order to be close to the world average top-quark mass [3], we use the top-quark mass dependence (presented above) to correct to a top-quark mass 172.5 GeV/c^2. We also include the top-quark mass-related systematic uncertainty corresponding to ±1.1 GeV/c^2 uncertainty on m_{top} [3]. The results of the dilepton and single lepton channels are statistically independent. There is a strong negative correlation of the statistical uncertainty between the f_0 and f_+ observables for both channels as mentioned above. The systematic uncertainties are theoretically dominated and are assumed to be 100% correlated between the measurements, with the exception of the method-specific systematic uncertainties (signal and background template statistics) which are treated as uncorrelated. The luminosity-related systematic uncertainty applies only to the dilepton measurement. For a given measurement, we assume that the f_0 and f_+ uncertainties are 100% anti-correlated for each systematic uncertainty category. Table III presents the full correlation matrix between the measurements and their weights in the combination. The combined result for the simultaneous measurement is $f_0 = 0.843 \pm 0.093$(stat)± 0.054(syst) and $f_+ = -0.155 \pm 0.052$(stat)± 0.039(syst). The combination has a χ^2 value of 0.99 for two degrees of freedom, corresponding to a p-value of 61% for consistency between the input measurements. The combined values of f_0 and f_+ have a correlation coefficient –0.81. We also combine the measurements of one polarization fraction when the other one is fixed to SM expected value. In this case, we arrive at $f_0 = 0.637 \pm 0.055$(stat) $\pm$ 0.047(syst) (f_+ is fixed) and $f_+ = -0.068 \pm 0.024$(stat)± 0.038(syst) (f_0 is fixed). The combination for f_0 (f_+) has a χ^2 of 1.04 (0.61) for one degree of freedom, corresponding to a p-value of 31% (44%) for consistency between the input

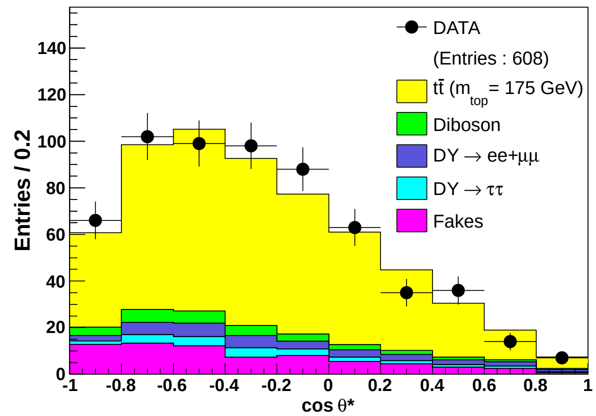

FIG. 2: The comparison of $\cos\theta^*$ distribution between data and the expected SM $t\bar{t}$ signal and background. Each event has two entries in the histogram.

TABLE III: The correlations between the measurements and their weights in the f_0 and f_+ combined result. The results from single lepton channel are labeled as 'LJ', the dilepton results as 'DIL'.

Measurement	Correlation matrix				Weight for f_0 (%)	Weight for f_+ (%)
LJf_0	1				80.6	−21.8
DILf_0	0.13	1			19.4	21.8
LJf_+	−0.72	−0.15	1		18.9	24.0
DILf_+	−0.12	−0.88	0.16	1	−18.9	76.0

measurements.

To summarize, we have performed the measurement of W boson polarization fractions in top-quark dilepton decays. We have also combined our dilepton measurement with our previous measurement in the single lepton channel. Our results are consistent with the SM expectations and do not require the introduction of new physics. They agree with the results obtained by the D0 collaboration [5] which are of comparable precision. Our method is also the first model-independent measurement of the W polarization in the dilepton channel from CDF.

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[8] CDF uses a cylindrical coordinate system with the z axis along the proton beam axis. Pseudorapidity is $\eta \equiv -\ln\tan(\theta/2)$, where θ is the polar angle relative to the proton beam direction and ϕ is the azimuthal angle while $p_T = |p|\sin\theta$, $E_T = E\sin\theta$.
[9] For the muons, transverse momentum p_T rather than transverse energy E_T is considered in the text.
[10] The missing transverse energy ($\vec{\not\!\!E}_T$) is defined by $\vec{\not\!\!E}_T = -\sum_i E_T^i \hat{n}_i$, where i denotes calorimeter tower number with $|\eta| < 2.5$, and $\hat{n}_i$ is a unit vector perpendicular to the beam axis and pointing at the ith calorimeter tower. We also define $\not\!\!E_T = |\vec{\not\!\!E}_T|$.
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